INVESTIGATION OF A MULTIPLE-SOURCE SCHLIEREN SYSTEM FOR APPLICATION TO A PERFORATED WALL WIND TUNNEL

By

M. Pindzola, PWT, ARO, Inc.

G. R. Mozer, Lt. USAF

April 1956

ARNOLD ENGINEERING DEVELOPMENT CENTER

AIR RESEARCH AND DEVELOPMENT COMMAND

US AF

AEDC-TR-56-1
ASTIA DOCUMENT NO.:
AD-87754

INVESTIGATION OF A MULTIPLE-SOURCE SCHLIEREN SYSTEM FOR APPLICATION TO A PERFORATED WALL WIND TUNNEL

by

M. Pindzola; PWT, ARO, Inc.

G. R. Mozer; Lt. USAF

April 1956

Contract No. AF 40(600)-620

CONTENTS

TABLE

ILLUSTRATIONS

SUMMARY

The use of a multiple-source schlieren system was studied for application to wind tunnels employing perforated walls. Visibility equations are derived showing the influence of geometrical parameters on the schlieren photograph background pattern for first one and then two tunnel walls. A uniformly illuminated background pattern is shown to be easily attained with a single perforated wall, but not with two identically perforated walls. A method of obtaining a uniformly illuminated background pattern for the two wall case by relocating the holes in one perforated tunnel wall is discussed. The use of an external source plate is shown to increase system sensitivity at no sacrifice in background pattern. The multiple-source schlieren system is also shown to be useful with transparent walls where the conventional system is unsatisfactory.

NOMENCLATURE

a	Hole spacing (distance between adjacent hole centers)
A	Area
d	Hole diameter
δ	Displacement of light ray
D	Lens diameter
F	Focal length
H	Height
N	Number of contributing holes
P	Distance in object space
V	Visibility number
W	Width across tunnel walls
x	Distance between second wall and object plane
θ	Angular deflection of a light ray
σ	Porosity (ratio of open to total area)

Subscripts

s	Source plane
o	Object plane
w	Plane of the second wall
sw	Single wall
tw	Two wall
ua	United Aircraft

Superscript

$'$	Conjugate conditions in the image space

INTRODUCTION

With the advent of perforated test section walls in transonic wind tunnels, the conventional type schlieren system has proved to be inadequate for schlieren observations. Photographs of the flow, obtained by using parallel light directly through the tunnel walls with the perforations aligned, give insufficient coverage of the flow field. The common practice of inserting plate glass windows into the tunnel walls is also unsatisfactory because flow through these closed portions of the walls is prohibited, resulting in objectionable flow disturbances.

The study of means of observing flow disturbances through perforated walls by the United Aircraft Research Laboratory (UAC) led to the application of the multiple-source, sharp-focusing schlieren system. The results of the UAC studies, as summarized in Ref. 1, led to their formulation of an empirical equation defining the critical geometric parameters of the system for such application.

As perforated walls will be employed in the Propulsion Wind Tunnel (PWT) at the Arnold Engineering Development Center, a study of such application was started in August 1954. Although this investigation involved the utilization of a multiple-source schlieren system in this particular wind tunnel, the design relationships which were established are of a general nature and should be applicable to any such system. This report was therefore prepared in order to more widely disseminate this information.

The authors wish to acknowledge the early work at AEDC on this subject by C. Link which laid the groundwork for the studies herein reported. The assistance in the experimental studies by B. A. Barwise and the suggestions of Dr. B. H. Goethert are also gratefully acknowledged.

CHARACTERISTICS OF A MULTIPLE-SOURCE SCHLIEREN SYSTEM

LAYOUT

A multiple-source, sharp-focusing schlieren system (Refs. 2, 3 and 4) consists of the components shown in Fig. 1.

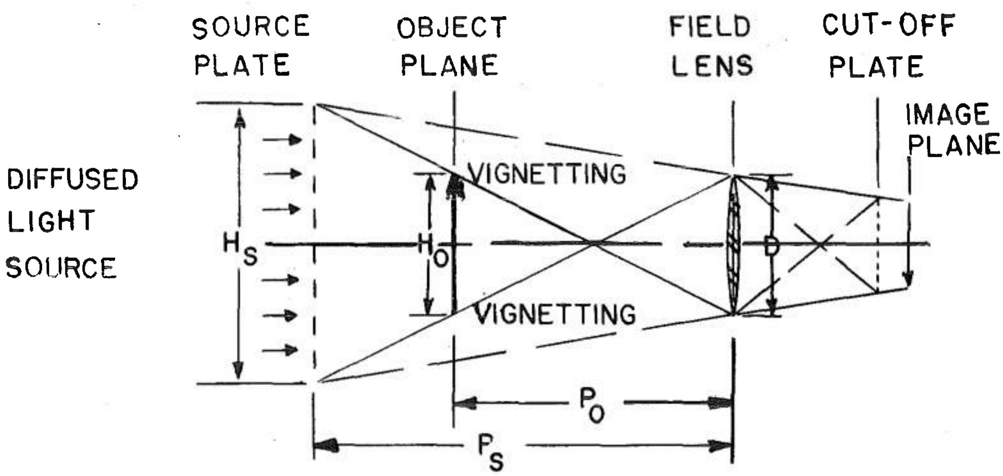


Fig. 1. Multiple-Source Schlieren System

A series of holes or slits illuminated by a source of diffused light serves as a source plate, in effect, as a multitude of small light sources. The camera side of the system consists of a field lens, a cutoff plate (a negative image of the source plate), and the image plane of the field in view.

SHARP FOCUSING

The sharp focusing property of a multiple-source schlieren system was pointed out in the early reports on this system (Refs. 2, 3 and 4). This property is dependent on the divergent rays of light from the object, with the focusing action increasing as the angle formed by these rays increases. These rays are converged by the lens, and the overlapping of the various light rays forms a final image. This property does not exist in a conventional schlieren system in which a single source of light is used.

FIELD SIZE

In contrast to a conventional schlieren system, in which the field of view can be no larger than the largest optic or mirror, the field of view in a multiple-source system is primarily dependent upon the size of the source plate. Uniform illumination of the field is obtained within the double cone between the source plate and the lens (see Fig. 1). In the remainder of the field, vignetting occurs as the edges of the field are approached. The size of the source plate required to prevent vignetting for a given size field, as pointed out in Ref. 3, is given by the equation:

$$H_s = (H_o + D)\frac{P_s}{P_o} - D \tag{1}$$

SENSITIVITY

The geometric parameters which have an effect on the sensitivity of a multiple-source system are derived in Ref. 1.

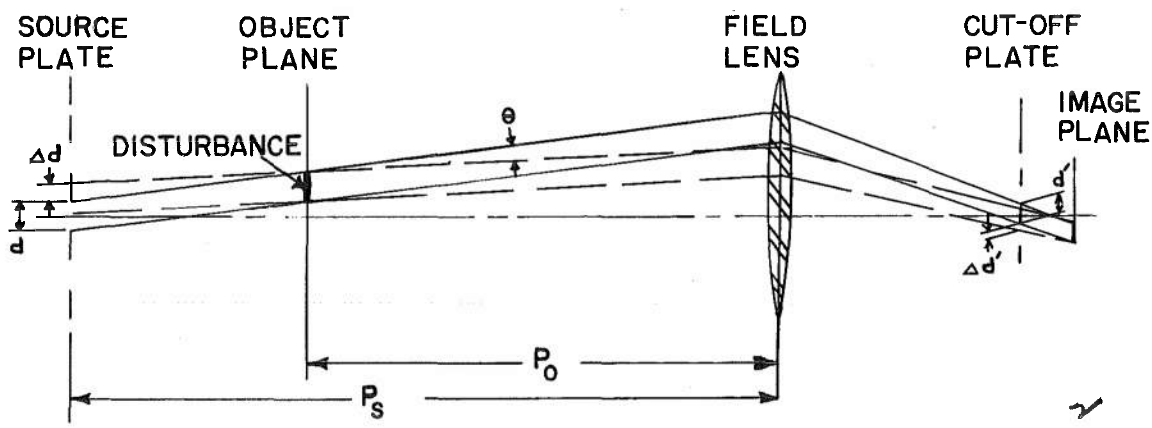


Fig. 2. Sensitivity Parameters for a Multiple-Source System

As can readily be concluded from consideration of Fig. 2, the range of the system is defined by:

$$\theta_{\max} = \frac{d}{P_s - P_o} \tag{2}$$

Consequently, the sensitivity of a system is a maximum when the range of the system matches the deflection range of the disturbances under observation. A decrease of the slit width or hole diameter below this value will result only in a reduction of the range of the system. In a multiple-source system, enough space should be provided between the

source holes or slits to prevent the most highly deflected rays from interfering with adjacent cutoff images.

As stated in Ref. 1, the displacement of light at the image of the source (δ') relative to the width of the image of the source (d') is a measure of the relative sensitivity of the system. From Fig. 2, it is evident that the ratio $\frac{\delta'}{d'}$ is equal to $\frac{\delta}{d}$, and that for small angles of deviation:

$$\delta = (P_s - P_o)\,\theta$$

giving:

$$\frac{\delta}{d} = \frac{\delta'}{d'} = \frac{(P_s - P_o)\,\theta}{d} = \frac{\theta}{\theta_{max}} \tag{3}$$

Therefore, the geometric parameters which affect the range or the relative sensitivity of a multiple-source schlieren system are the distance between the source plate and object plane ($P_s - P_o$) and the diameter (d) or width, as the case may be, of the individual light sources. By replacing ($P_s - P_o$) in the equation by the focal length (F) of the principal optic in a conventional system, the resulting expression has the same form as the equation for the relative sensitivity of a conventional schlieren setup.

As noted in Ref. 1, the increase in illumination is directly proportional to the displacement of the light ray for a slit source only. For a circular light source, the increase in illumination is no longer a linear function of displacement.

LIMITATIONS

Because of the divergence of the light rays in a multiple-source system, difficulty is encountered in the observance of flow phenomena along the surfaces of two-dimensional models. As the surface of the model is approached, the number of light rays contributing to form the image of boundary disturbances is successively reduced resulting in insufficient illumination and therefore poor resolution of boundary phenomena.

BACKGROUND PATTERN FOR A SINGLE WALL

Studies of the adaptation of the multiple-source schlieren system to the Propulsion Wind Tunnel were initiated by utilizing one of the tunnel walls as the source plate with the other wall removed. The objective was to define the critical parameters of the system which affect the background lighting as produced by the multitude of point light sources (perforated holes) at various planes throughout the viewing field.

ANALYTICAL DEVELOPMENT

The analytical development of the problem, as suggested by Dr. Goethert, can most easily be shown with reference to Fig. 3.

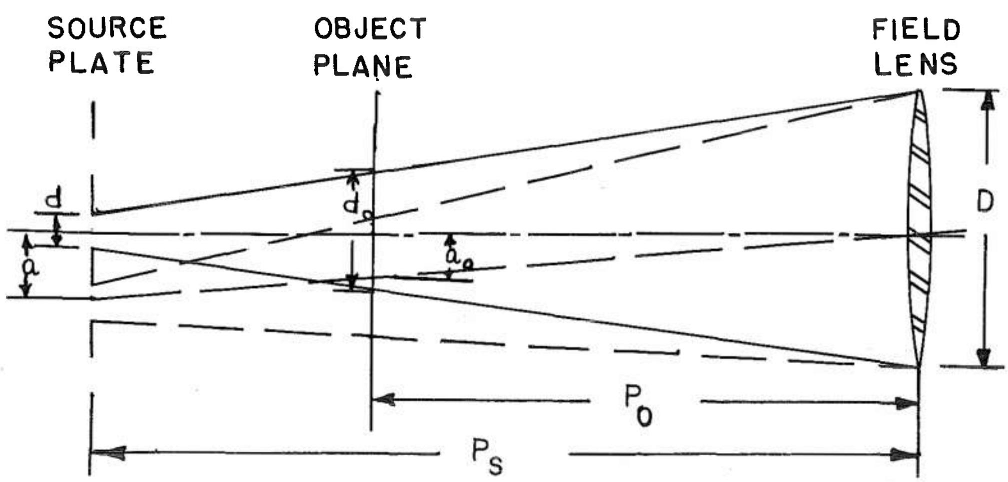


Fig. 3. Light Ray Pattern with a Single Wall

The diffused diameter of a single hole at any object plane of the field of view is:

$$d_o = \frac{D\,(P_s - P_o) + d\,P_o}{P_s} \tag{4}$$

When a number of holes are considered, a visibility parameter (V_{sw}) can be introduced in the form:

$$V_{sw} = \frac{a_o}{d_o}$$

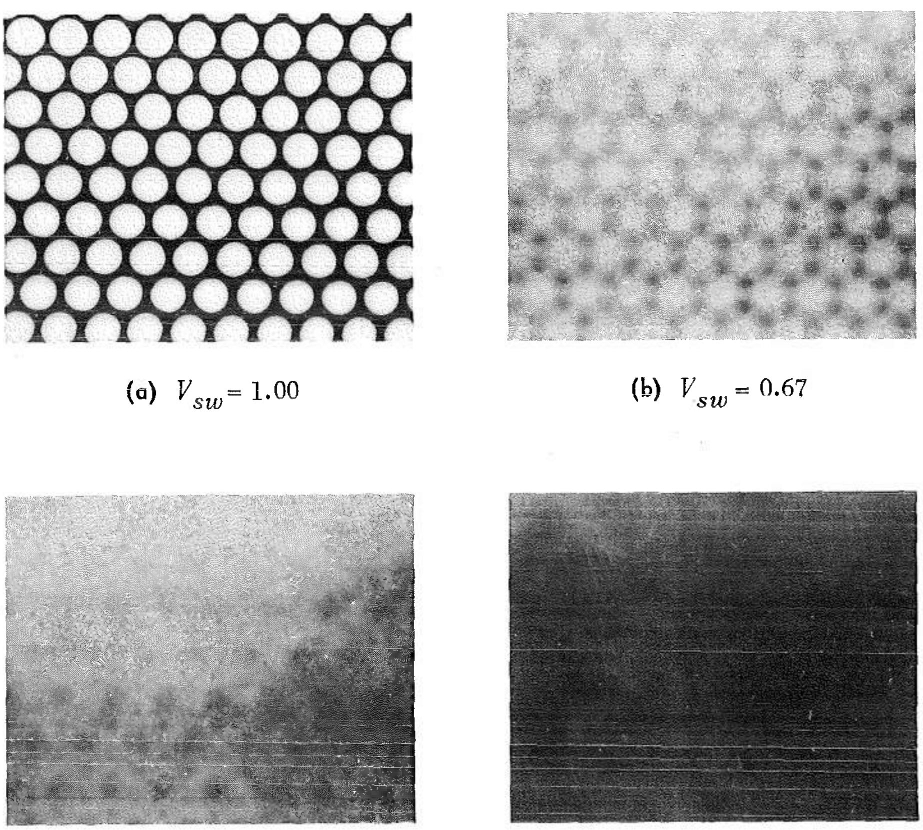
since, $a_o = \frac{a P_o}{P_s}$

then, $$V_{sw} = \frac{a/d}{1 + \left(\frac{P_s - P_o}{P_o}\right) \cdot \frac{D}{d}} \quad (5)$$

A visibility parameter of 1.0 should give a pattern in which the images of the holes just begin to touch. A parameter on the order of 0.5 should give sufficient overlapping of the hole images to produce a uniform background pattern.

EXPERIMENTAL VERIFICATION

An experimental check of this visibility equation was made by varying the ratio of $\frac{P_s - P_o}{P_o}$ in order to give a range of typical values of the visibility parameter. The series of photographs obtained is shown in Fig. 4.



(a) $V_{sw} = 1.00$ (b) $V_{sw} = 0.67$

(c) $V_{sw} = 0.43$ (d) $V_{sw} = 0.21$

Fig. 4. Background Patterns for a Single Wall

Although the images of the holes should just touch for $V_{sw} = 1.00$ (see Fig. 4a), the decrease in light intensity as the edge of the hole is approached is evidently enough not to expose the photographic film. As seen from the photographs, a satisfactory background pattern is obtained with a parameter below 0.5. Use of a single wall as a multiple light source plate should cause no difficulty from the point of view of a background pattern since most applications should allow values below 0.5 to be easily attained.

BACKGROUND PATTERN FOR TWO WALLS

After the studies with a single wall, the other tunnel wall was added to the system. This configuration corresponds to that studied in some detail by the United Aircraft Research Laboratory (Ref. 1). The objective in this case also was to define the critical geometric parameters of the system affecting the background lighting at various planes between the two walls.

UNITED AIRCRAFT STUDIES

United Aircraft conducted an extensive experimental program to define the critical geometric parameters which affect the performance of a multiple-source system using the two-wall configuration. From these tests, an empirical equation was developed in terms of a visibility number. This equation, developed for a wall of 22.5-percent porosity, a 30° coplaner rotation of one wall with respect to the other, and the object plane at the centerplane of the tunnel, is:

$$V_{ua} = \left(\frac{d}{D}\right)^{.71} \frac{P_s}{W} \tag{6}$$

A decrease in the value of this visibility number improved the system performance to the extent that values in the order of 0.10 to 0.20 gave acceptable results.

ANALYTICAL DEVELOPMENT

For the studies reported herein, the analytical development of a similar visibility equation was attempted. As Fig. 5 shows, the addition of a second wall breaks up the light cone from each hole in the source plate into a number of pencil rays.

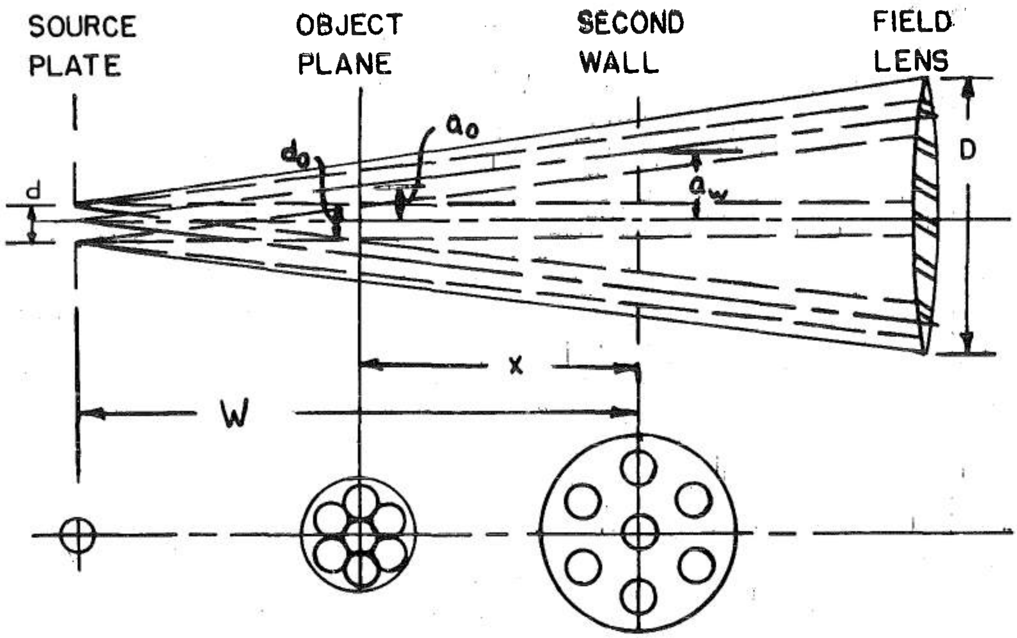


Fig. 5. Light Ray Pattern with Two Walls

The cross-sectional diameter (d_o) of these individual rays of light for plates of the same hole size is essentially equal to the diameter of the holes; and the spacing between the holes at any object plane (a_o) is equal to $\left(1 - \frac{x}{W}\right)$ times the hole spacing at the second wall (a_w), that is:

$$d_o = d \tag{7}$$

$$a_o = \left(1 - \frac{x}{W}\right) a_w \tag{8}$$

When more than a single hole is taken into consideration, it can be shown that a number of rays tend to stack upon a single light spot at the object plane depending upon the distance $\frac{x}{W}$ and the wall rotation. As shown in the following development, the problem thus becomes one of (1) calculating the number of rays passing through a single light spot at the object plane, and (2) defining a means of uniformly distributing these rays over this plane.

For the solution of the first part of the problem, reference is made to Fig. 6. With the hole patterns in the walls identically oriented, the

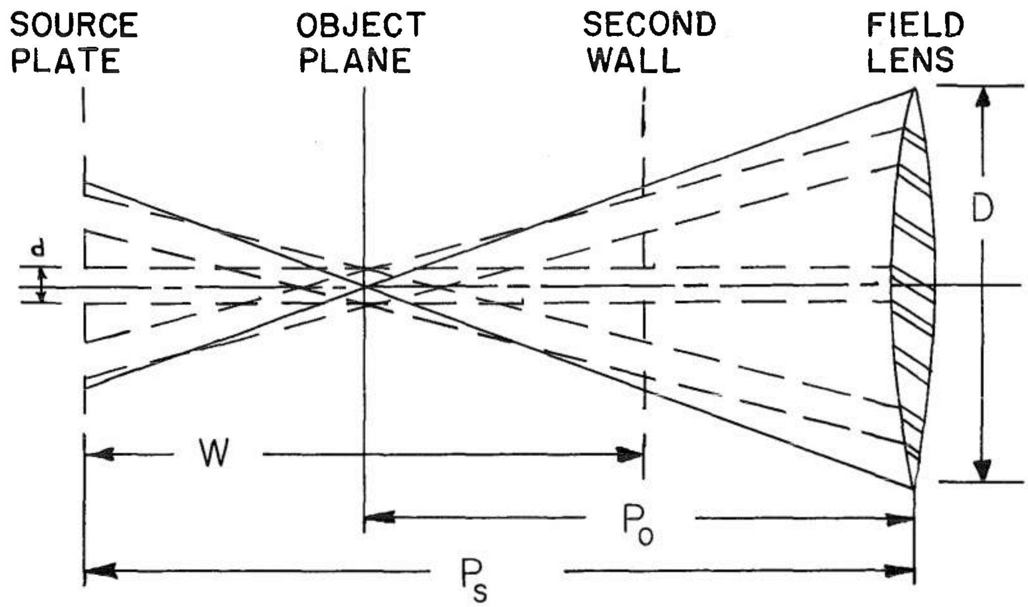


Fig. 6. Rays Contributing to Centerplane Background Pattern

number of light rays passing through a single light spot at the center-plane between the walls and lying within the double cone subtended by the lens diameter is seen to be equal to the number of holes lying within the smaller area at either wall within this cone. This area is given by:

$$A \doteq \frac{\pi D^2}{4} \left[\frac{W - (P_s - P_o)}{P_o} \right]^2 \qquad \text{when } \frac{x}{W} \leq \tfrac{1}{2} \tag{9a}$$

$$A = \frac{\pi D^2}{4} \left(\frac{P_s - P_o}{P_o} \right)^2 \qquad \text{when } \frac{x}{W} \geq \tfrac{1}{2} \tag{9b}$$

$$A = \frac{\pi D^2 W^2}{16 P_o^2} \qquad \text{when } \frac{x}{W} = \tfrac{1}{2} \tag{9c}$$

and since the number of holes in a given area of perforated wall with a triangular hole pattern is:

$$\frac{N}{A} = \frac{4\sigma}{\pi d^2} \tag{10}$$

the number of holes in this area and, therefore, the number of light rays passing through a single light spot at the object plane is:

$$N = \frac{\sigma D^2}{d^2} \left[\frac{W - (P_S - P_O)}{P_O} \right]^2 \qquad \text{when} \quad \frac{x}{W} \leq ½ \qquad (11a)$$

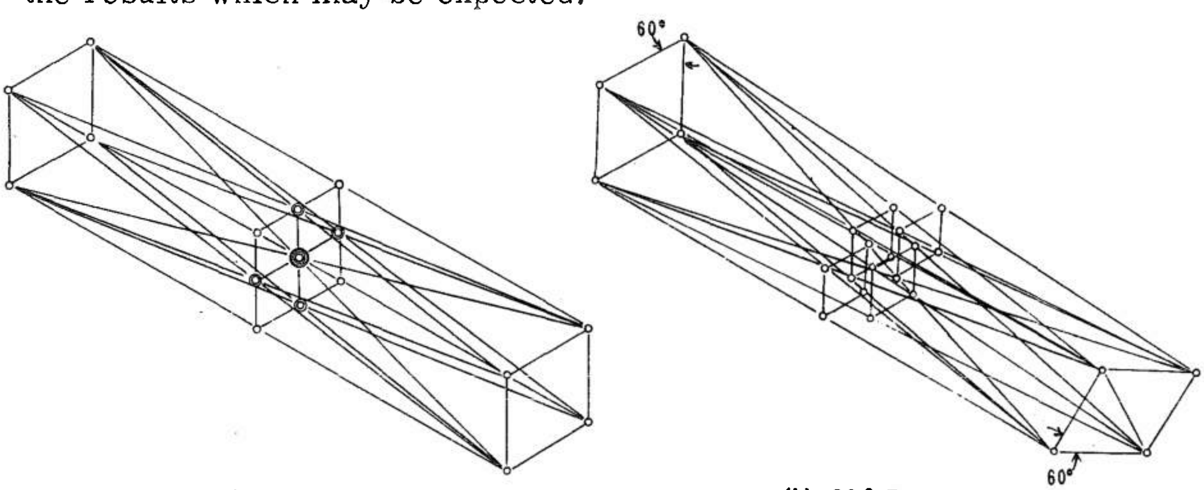
$$N = \frac{\sigma D^2}{d^2} \left(\frac{P_S - P_O}{P_O} \right)^2 \qquad \text{when} \quad \frac{x}{W} \geq ½ \qquad (11b)$$

$$N = \frac{\sigma D^2 W^2}{4 d^2 P_O^2} \qquad \text{when} \quad \frac{x}{W} = ½ \qquad (11c)$$

It should be noted that the above calculated hole number corresponds to a perforated wall area of such a size that all rays passing through it are captured by the lens.

With respect to the second part of the problem, a method is desired of defining a means of locating the perforated holes in the two walls so that a uniform distribution of the light rays over a unit area is attained. The following discussion indicates the results which can be expected using two walls with an identical hole pattern, and presents a method of redistributing the holes in the second wall to obtain a uniformly illuminated background.

For the case of two walls with a repeating, identical hole pattern (triangular for the example discussed), the ray traces in Fig. 7 show the results which may be expected.



(a) No Rotation (b) 30° Rotation

Fig. 7. Ray Traces with Identical Hole Patterns

With no rotation of the hole pattern of one wall with respect to the other (see Fig. 7a), a centerplane pattern identical to that of the walls is obtained with the spacing between holes (a_o) equal to one-half that of the wall plates. It can be shown that the addition of more holes to either plate will add more spots, according to the wall pattern, to the centerplane and further stacking of rays at additional spots. The maximum number of stacked rays at a single spot will be determined by and will be equal to the number of holes in the wall with the minimum number of contributing holes. In taking the case of two identical wall plates where the hole spacing (a) is twice the hole diameter (d), a visibility number ($V_{tw} = a_o/d_o$) equal to 1.0 is obtained, since as stated previously $a_o = a/2$ and $d_o = d$. Thus some means of unstacking the rays and reducing a_o is required.

A 30° rotation of one wall with respect to the other for the pattern shown (Fig. 7b) will unstack the light rays, but due to the symmetry of the wall hole patterns a repeating centerplane pattern will be obtained as shown. Furthermore, unequal spaces, a_o, between various pairs of holes in the pattern at the centerplane cause a nonuniform illumination of the background. Since it can be shown that the rays are unstacked to the greatest extent at the centerplane for a value of 30° between the 0° and 60° extremes, the 30° value should give the most uniform pattern.

Another method of unstacking the light rays is shown in Fig. 8. In this case the hole spacing between the four holes shown on the second wall plate is reduced to one-half that of the source plate, giving a centerplane pattern identical to that of the source plate, but at one-fourth the hole spacing. Thus, for a wall of 22.5-percent porosity, the visibility number (V_{tw}) is reduced to 0.5. A control of the visibility number is therefore obtained by a reduction in the hole spacing of the second wall. It can also be shown that a reduction of the hole pattern in the second wall to one-third in the case of nine holes, one-fourth in the case of sixteen holes, etc., will give a uniformly spaced centerplane pattern with no stacking of rays. The visibility number for these specific cases can therefore be obtained.

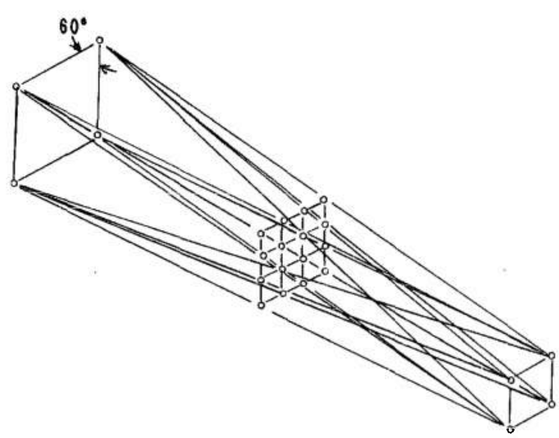


Fig. 8. Ray Traces with a Reduced Hole Pattern

Since, $a_w = \dfrac{a}{\sqrt{N}}$

then, $a_o = (1 - \dfrac{x}{W})\ a_w = \dfrac{a}{2\sqrt{N}}$ when $\dfrac{x}{W} = \frac{1}{2}$

and with, $d_o = d$

$$V_{tw} = \frac{a_o}{d_o} = \frac{a}{2\,d\,\sqrt{N}} \qquad \text{when } \frac{x}{W} = \frac{1}{2} \tag{12}$$

For the general case at any object plane, it can be shown that the hole spacing in the second wall required to produce a uniform background pattern with no stacking of rays is given by the equation:

$$a_w = \frac{\frac{x}{W}}{1 - \frac{x}{W}} \cdot \frac{a}{\sqrt{N}} \tag{13}$$

which, when combined with Eq. (8), gives:

$$a_o = \frac{x}{W} \cdot \frac{a}{\sqrt{N}} \tag{14}$$

The general visibility equation can therefore be expressed as:

$$V_{tw} = \frac{a_o}{d_o} = \frac{x}{W} \cdot \frac{a}{d\,\sqrt{N}} \tag{15}$$

A reduction in the hole spacing of the second wall, as indicated in the previous discussion, becomes impossible in almost all cases since the holes would overlap. This reduction in hole spacing is not a necessity, however, since the main point of concern is that the holes are relocated in the same positions relative to the original hole pattern as obtained by reducing the pattern. This relocated pattern for the case utilizing 16 contributing holes is shown in Fig. 9. The reduced and original hole patterns are also shown for comparison.

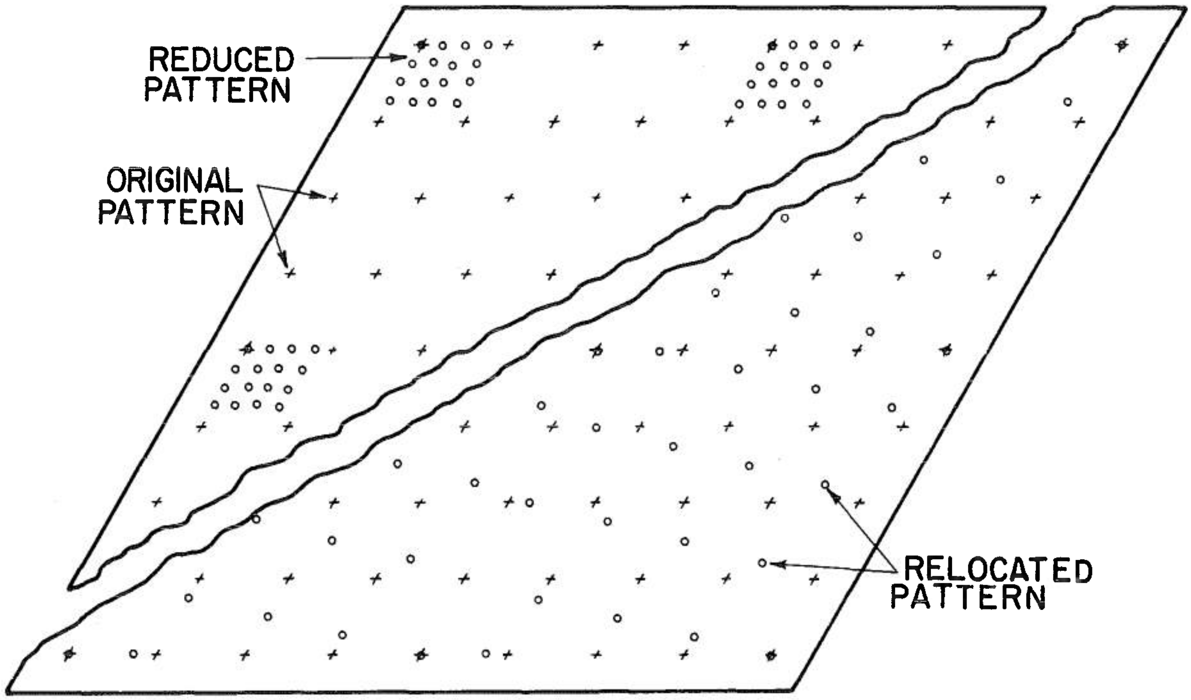


Fig. 9. Relocated Hole Patterns for 16 Contributing Holes

In order to obtain a relationship between the visibility parameter given by Eq. (15) and the geometric parameters of the system, the dependence of N in Eq. (15) upon these parameters is required. Equation (11) gives the parameters upon which N depends for a wall with the original hole pattern. From Fig. 9 it can be seen that the derivation of Eq. (11) would also apply, to a very close approximation, to a wall with a relocated hole pattern. Therefore, a combination of Eqs. (11) and (15) gives the geometric parameters which affect the background pattern for the relocated hole pattern:

$$V_{tw} = \frac{x}{W} \cdot \frac{a \quad P_o}{\sqrt{\sigma} \quad D \quad [W - (P_s - P_o)]} \qquad \text{when } \frac{x}{W} \leq ½ \tag{16a}$$

$$V_{tw} = \frac{x}{W} \cdot \frac{a \quad P_o}{\sqrt{\sigma} \quad D \ (P_s - P_o)} \qquad \text{when } \frac{x}{W} \geq ½ \tag{16b}$$

$$V_{tw} = \frac{a \quad P_o}{\sqrt{\sigma} \quad DW} \qquad \text{when } \frac{x}{W} = ½ \tag{16c}$$

since the porosity for a plate with a triangular pattern of holes can be expressed as:

$$\sigma = \frac{\pi d^2}{2\sqrt{3}\, a^2} \tag{17}$$

Other forms of the visibility equation are:

$$V_{tw} = \sqrt[4]{\frac{12}{\pi^2}} \cdot \frac{x}{W} \cdot \frac{a^2 P_o}{d\, D\, [W - (P_s - P_o)]} \qquad \text{when } \frac{x}{W} \leq \tfrac{1}{2} \tag{18a}$$

$$V_{tw} = \sqrt[4]{\frac{12}{\pi^2}} \cdot \frac{x}{W} \cdot \frac{a^2 P_o}{d\, D\, (P_s - P_o)} \qquad \text{when } \frac{x}{W} \geq \tfrac{1}{2} \tag{18b}$$

$$V_{tw} = \sqrt[4]{\frac{12}{\pi^2}} \cdot \frac{a^2 P_o}{d\, D\, W} \qquad \text{when } \frac{x}{W} = \tfrac{1}{2} \tag{18c}$$

For the case of the reduced hole pattern, assuming that the holes did not overlap and that the lens is placed at the second wall, the lens area and therefore diameter (D) could be decreased to the same extent as the area of the hole pattern. However, when the lens is displaced some distance from the wall and more than a single set of reduced holes is required to illuminate the object field (as will generally be the case), then Eq. (11) will again define the geometric parameters which affect N. Equations (16) and (18) would therefore apply to this latter case also.

For the case of determining the geometric parameters for the centerplanc at a fixed porosity (for example, 22.5-percent as in the UAC tests, Ref. 1), the visibility equation is:

$$V_{tw} = \left(\frac{2}{\sqrt{.225}}\right)\left(\frac{d}{D}\ \frac{P_o}{W}\right) \tag{19}$$

The similarity between this equation and that empirically derived by UAC (see Eq. (6)) is noted.

By means of additional geometric analysis, it can also be shown that a uniform background pattern can be obtained for a triangular hole pattern in which the number of contributing holes is other than the square of an integer. The method of locating the holes in these cases involves a rotation of the pattern as well as a reduction in hole spacing

according to Eq. (13). Equations (15), (16) and (18) also hold for these cases. A listing of the number of contributing holes (here shown only up to a maximum of 25 holes) which can be uniformly distributed and the resulting visibility number at the centerplane for typical a/d ratios is made in Table 1 for reference.

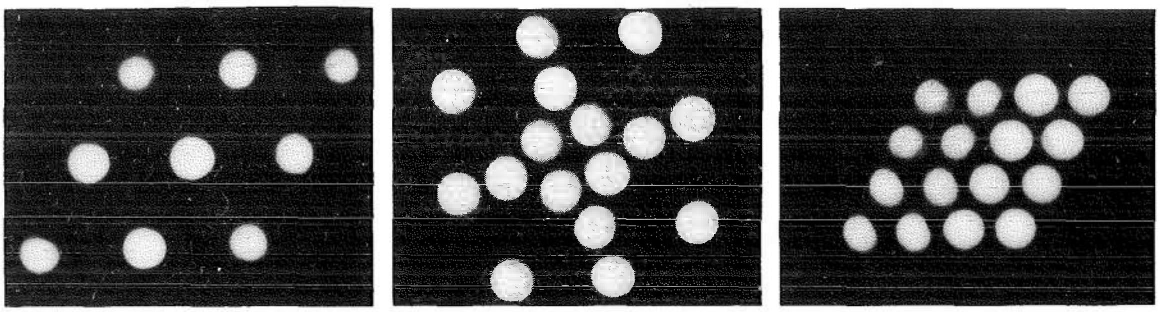
TABLE 1

Relationship between the Number of Contributing Holes and the Visibility Number at the Centerplane for Typical a/d Ratios

Number of Holes, N	Visibility Number, V_{tw}		
	$a/d = 3$	$a/d = 2$	$a/d = 1.67$
1	1.500	1.000	0.833
3	0.866	0.577	0.481
4	0.750	0.500	0.417
7	0.567	0.378	0.315
9	0.500	0.333	0.278
12	0.433	0.289	0.241
13	0.416	0.277	0.231
16	0.375	0.250	0.208
19	0.344	0.230	0.191
21	0.327	0.218	0.182
25	0.300	0.200	0.167

EXPERIMENTAL VERIFICATION

In order to demonstrate the means of unstacking the light rays previously discussed, a test configuration was chosen with four contributing holes at a hole spacing to hole diameter ratio of 4. The patterns obtained are shown in Fig. 10.

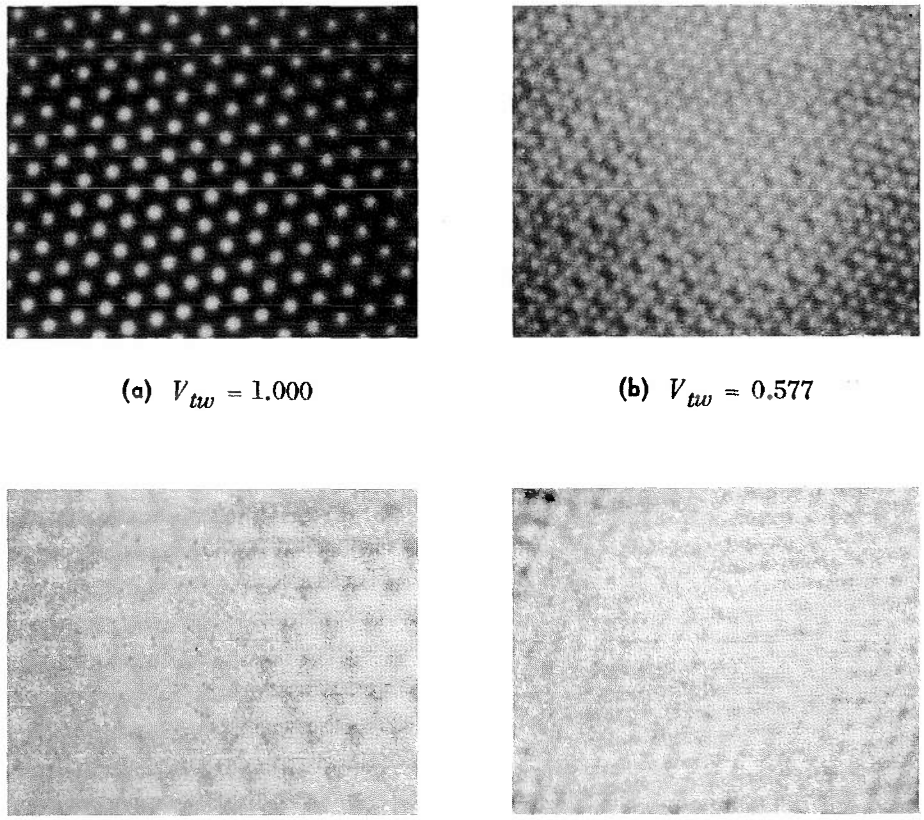


(a) 0° Rotation (b) 90° Rotation (c) Relocated Holes

Fig. 10. Centerplane Light Spot Patterns with Two Walls

Figure 10a shows the centerplane pattern obtained with the walls identically oriented (0° rotation). The light spots are spaced at one-half of the spacing at the wall and are stacked as shown in Fig. 7a. In Fig. 10b, the second wall was rotated 90°, which resulted in an unstacking of the rays; however, the pattern is nonuniform. Figure 10c demonstrates the uniform pattern which can be obtained by reducing the hole spacing in the second wall by a factor of 2, as discussed previously.

As pointed out previously and tabulated in Table 1, a wide choice of visibility number and therefore background pattern is attainable with a source plate of a 60° triangular hole pattern. The improvement in background pattern for a wall of 22.5-percent porosity as the number of contributing holes is increased is shown in the series of photographs in Fig. 11.



(a) $V_{tw} = 1.000$

(b) $V_{tw} = 0.577$

(c) $V_{tw} = 0.378$

(d) $V_{tw} = 0.250$

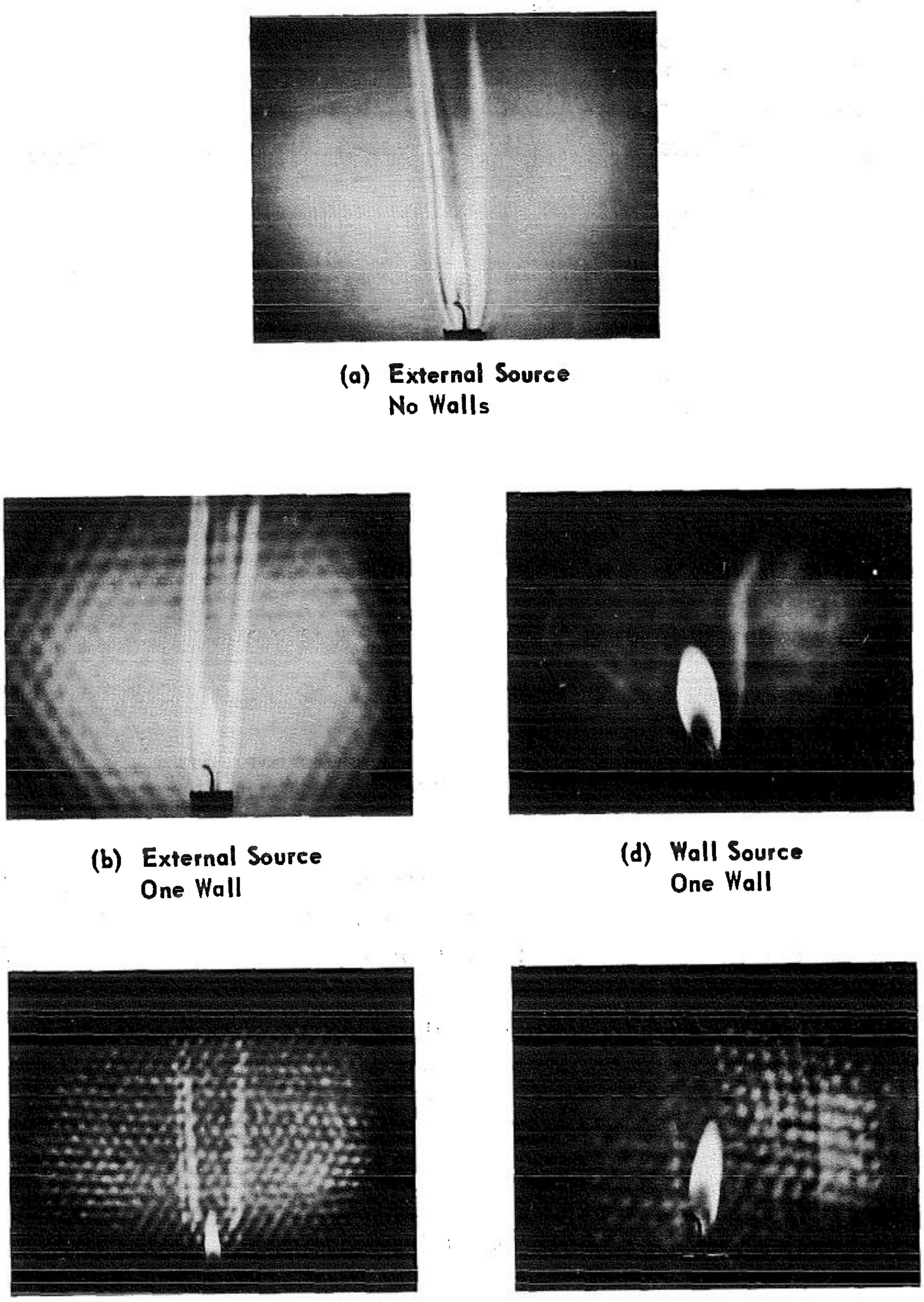
Fig. 11. Centerplane Background Patterns with Relocated Hole Patterns

Fig. 11a was obtained with only one contributing hole, and therefore no change was required in the hole locations of the second wall. Figure 11d was obtained with 16 contributing holes with the second wall drilled according to the relocated hole pattern shown in Fig. 9. Figures 11b and 11c were obtained in turn with 3-hole and 7-hole relocated patterns. As in the case of the single wall, a visibility parameter of less than 0.50 should generally be attainable. The resulting background pattern should in most cases, therefore, prove acceptable.

SENSITIVITY CONSIDERATIONS

In the application of a multiple-source schlieren system to any large wind tunnel, the use of a tunnel wall as the source plate would require smaller holes than would normally be used in order to obtain sufficient sensitivity. A modification to the system was therefore

tested in which a source plate external to the tunnel wall plates was added. The use of this additional plate offered the two-fold advantage of an increased distance between the source and object plane ($P_s - P_o$) as well as the possibility of using small hole sizes or even narrow slits in the source plate.



(a) External Source
No Walls

(b) External Source
One Wall

(d) Wall Source
One Wall

(c) External Source
Two Walls

(e) Wall Source
Two Walls

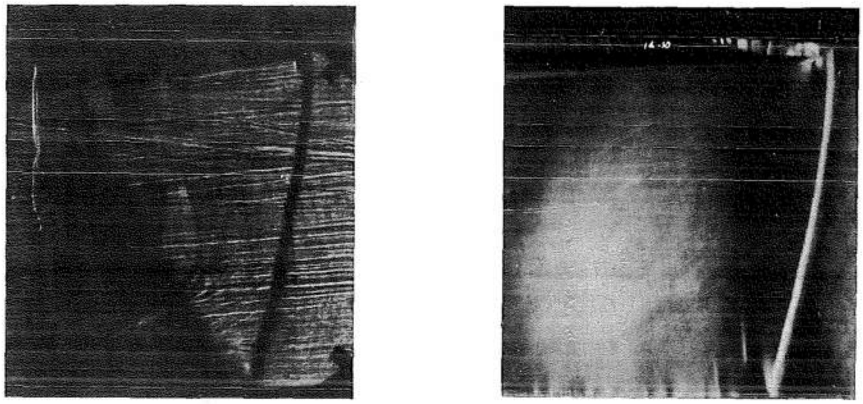
Fig. 12. Comparison of External Source with Wall Source

Figure 12 presents the results of a test of the modified system with a candle flame used as the disturbance. The external source was a plate consisting of perforated slits placed to give a total range of 1.2 minutes as compared to 32 minutes when the far wall was used as the source plate. Figure 12a was obtained with no simulated tunnel walls; and because of the large distance between the source plate and object plane, the background pattern of the source plate is not noticeable. An excellent definition of the heat waves from the candle flame is obtained. For the single wall cases, Figs. 12b and 12d, the resulting background visibility number (V_{sw}) is 0.21. Since the cutoff plate used in the configuration to obtain Fig. 12d obscures a portion of the diffused hole image, a definite nonuniformity in the background pattern of this picture can be noted. The heat waves are still well defined with an external source whereas definition with the wall source is quite poor. The background visibility number (V_{tw}) for the two wall cases (see Figs. 12c and 12e) is 0.25. The effect of the cutoff plate can again be noted in Fig. 12e. A comparison of the definition of the heat waves for the cases with two walls again shows an appreciable gain in sensitivity using an external source.

The use of an external source plate thus offers a convenient means of improving the sensitivity of a system when applied to a tunnel in which the parameters which affect sensitivity are not compatible with the sensitivity requirements. This setup also allows mounting the source plate independent of the tunnel walls, thus increasing its adaptability to various tunnel and optical configurations. Caution should be exercised, however, when the sensitivity parameters are changed towards increased sensitivity, since the physical alignment of the cutoff plate becomes more difficult.

TRANSPARENT WALL APPLICATION

Because of its sharp focusing property, the multiple-source schlieren system offers a convenient means of observing flow disturbances through transparent material of poor optical quality, such as inexpensive plate glass or various forms of plexiglass. As in the case of the holes in perforated walls, the striae in the walls are sufficiently out-of-focus so as not to interfere with the observation of the flow disturbances under study.



(a) Conventional Schlieren System (b) Multiple-Source System

Fig. 13. Comparative Schlieren Picture through a Combination of Ordinary Plate Glass and Plexiglass Windows

Figure 13 shows comparative schlieren photographs of flow disturbances in the Transonic Model Tunnel at AEDC, taken with conventional and multiple-source schlieren systems through a combination of ordinary plate glass and plexiglass tunnel walls. The advantage of the multiple-source system is readily apparent.

CONCLUSIONS

The investigation of the application of a multiple-source schlieren system to perforated wall wind tunnels has led to the following conclusions:

1. The background pattern for a single wall of triangular hole pattern when used as the source plate in a multiple-source schlieren system is a function of the ratios of the hole spacing to hole diameter, of the lens-to-hole diameters, and of the distance between the source and object to the distance between the lens and object.

2. A uniformly illuminated background pattern with no stacking of light rays can be attained at only a single plane between two walls of identical hole pattern and a fixed number of contributing holes. An acceptable pattern can be approached at other planes, however, with a coplanar rotation of one wall with respect to the other if a sufficient number of contributing rays per unit area is utilized.

3. By relocating the holes of the second wall in the two wall case, a uniformly illuminated background pattern at the object plane can be attained. This pattern is a function of the ratio of the hole spacing to hole diameter of the source plate, the number of contributing rays per unit area, and the position of the object plane with respect to the walls.

4. The use of a source plate external to the tunnel walls offers the possibility of increasing system sensitivity.

5. The multiple-source schlieren system can be used through transparent tunnel walls of poor optical quality where a conventional system is unsatisfactory.

REFERENCES

1. Behun, E., "A Schlieren System for Perforated Wall Type Transonic Wind Tunnels." WADC Technical Report 54-511, December 1954.

2. Burton, Ralph A., "A Modified Schlieren Apparatus for Large Areas of Field." Journal of the Optical Society of America, vol. 39, no. 11, November 1949, pp. 907-908.

3. Fish, R. W. and Parnham, K., "Focusing Schlieren Systems." CP54, ARC 13865, November 1950.

4. Kantrowitz, Arthur and Trimpi, Robert L., Cornell University, "A Sharp-Focusing Schlieren System." Journal of the Aeronautical Sciences, vol. 17, no. 5, May 1950, pp. 311-314.